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Evapotranspiration of annual and perennial biofuel crops in a variable climate

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Abstract

Eddy covariance measurements were made in seven fields in the Midwest US over four years (including the 2012 drought year) to estimate evapotranspiration (ET) of newly established rain-fed cellulosic and grain biofuel crops. Four of the converted fields had been managed as grasslands under the USDA Conservation Reserve Program (CRP) for 22 years and three had been in conventional agriculture (AGR) soybean/corn rotation prior to conversion. In 2009, all sites were planted to no-till soybean except one CRP grassland that was left unchanged as a reference site; in 2010 three of the former CRP sites and the three former AGR sites were planted to annual (corn) and perennial (switchgrass and mixed-prairie) grasslands. The annual ET over the four years ranged from 45 to 77% (mean=60%) of the annual precipitation (848-1063 mm; Nov-Oct), with the unconverted CRP grassland having the highest ET (622-706 mm). In the fields converted to annual and perennial crops, the annual ET ranged between 480 and 639 mm despite the large variations in growing-season precipitation and in soil water contents, which had strong effects on regional crop yields. Results suggest that in this humid temperate climate, which represents the US Corn Belt, water use by annual and perennial crops is not greatly different across years with highly variable precipitation and soil water availability. Therefore, large-scale conversion of row crops to perennial biofuel cropping systems may not strongly alter terrestrial water balances.

Key words: cellulosic biofuel crops, grasslands, water use, land use conversion, eddy covariance, Conservation Reserve Program, conventional agriculture

INTRODUCTION

Land is increasingly being converted into biofuel crop production, both globally and nationally, in response to increased demand for biofuel feedstock. In the United States this is mainly driven by legislative and regulatory developments that mandate use of biofuel crops as a renewable liquid transportation fuel source. For example, the US Energy Independence and Security Act of 2007 set a target of 136 billion liters of ethanol biofuel to be produced by 2022, with cellulosic feedstocks expected to contribute 61 billion liters. The goals of biofuel crop production are to reduce imported oil demand, stabilize energy prices, and mitigate climate change (Sims *et al*., 2006; Robertson *et al*., 2008; Tan *et al*., 2008).

The large area of land needed to meet cellulosic biofuel crop production goals will come from converting existing conventional cropland used for food and feed, and from converting previously uncultivated lands such as forests and grasslands (Fargione *et al*., 2010, Gelfand *et al*., 2013). In the US, grasslands formerly abandoned by agriculture and protected in the USDA's Conservation Reserve Program (CRP) are increasingly being converted into annual biofuel cropping systems, mainly corn (Secchi *et al*., 2009; Hellerstein and Malcolm, 2011; Wright and Wimberly, 2013). Such a massive land conversion may potentially result in unintended consequences such as increased land competition with food and feed production (Rathmann *et al*., 2010), loss of wildlife habitat (Stephens *et al*., 2008; Claassen *et al*., 2011; Wright and Wimberly, 2013), increased soil erosion (Montgomery, 2007), and declines in water quality (Love and Nejadhashemi, 2011). In addition, there is growing evidence that increases in carbon dioxide and nitrous oxide emissions can result from land conversion, incurring a greenhouse gas (GHG) "debt" that takes many years to pay back (Fargione *et al*., 2008; Gelfand *et al*., 2011; Ruan and Robertson, 2013).

The consequences of such land conversion to biofuel production for ecosystem-level water balance have been less investigated, and depend on the specific crop and on the ecosystem it replaces (Robertson *et al*., 2011). Groundwater recharge may be reduced upon conversion from annual to perennial crops because perennial crops have longer growing seasons and thus a longer period of water demand that may potentially be met by drawing water from deeper layers (Schilling *et al*., 2008; Asbjornsen *et al*., 2014). Conversely, because the land is not tilled and roots and litter remain on the soil surface, overland runoff may decrease, resulting in higher infiltration rates and reduced stream nitrogen and phosphorus loading and soil erosion losses (Schilling *et al*., 2008; McIsaac *et al*., 2010).

In general, changes in water use due to land use conversion affect carbon and nutrient cycles and GHG exchanges between the soil and the atmosphere. Large-scale land conversion to biofuel cropping systems with different water demands may therefore influence groundwater recharge, streamflow, GHG balances, the vertical structure of the atmospheric boundary layer, and other hydrological and climatological processes (Pielke *et al*., 1998; Wever *et al*., 2002; Wilson *et al*., 2002a; Humphreys *et al*., 2003).

The objective of this study is to examine the potential water implications of biofuel crop production during the conversion year and first three years of crop establishment. We measured biofuel crop water use over four years using eddy covariance measurements in three cropping systems grown as biofuel (corn, switchgrass and mixed prairie) and in a CRP grassland in southwest Michigan (USA), within the northeastern part of the Midwest Corn Belt. Our study sites are representative of rain-fed agricultural regions in temperate climates that supply much of the world's food. Water use by these annual and perennial cropping systems is compared across a range of wetter and drier years that produced unusually high and low crop yields in the region.

We hypothesize that perennial crops grown as cellulosic biofuel feedstocks would require more water than annual corn grown for food or biofuel because of their longer growing seasons and more extensive root development. In addition to its relevance to biofuel crop production, these measurements help constrain evapotranspiration (ET) rates from humid terrestrial biomes, which remain a source of uncertainty in global climate change models (Jasechko *et al*., 2013).

MATERIALS AND METHODS

Site description

The study was conducted at the Kellogg Biological Station Long-term Ecological Research site of Michigan State University, located in southwest Michigan (42°24' N, 85°24' W, 288 masl). The study area and experimental design were previously described by Bhardwaj *et al*. (2011) and Zenone *et al*. (2011, 2013). The region has a humid, continental temperate climate with mean annual air temperature of 9.9 ^{o}C and mean annual precipitation of 1027 mm (1981–2010; Michigan State Climatologist’s Office, 2013). Precipitation occurs throughout the year and on average is equally distributed through the growing season. The soils at all experimental fields are moderately to slightly acidic, well-drained sandy loams classified as Typic Hapludalfs according to the USDA soil classification (Thoen, 1990). Physical and chemical properties of the soils are presented in Table 1. The growing season is generally from about 15 May through 15 October (Day of year (DOY) 135-288) in this region.

Seven fields (9 to 21 ha) were converted for biofuel production as part of sustainability research of the US Department of Energy’s Great Lakes Bioenergy Research Center (GLBRC). Prior to land use conversion, four of the seven fields had been managed under the CRP since 1987 as grasslands dominated by smooth brome grass (*Bromus inermis* Leyss), a cool-season

Table 1. Soil physical and chemical properties for the top 0.25 m of the soil profile at each study site in 2008 just before conversion. Fields previously managed as grasslands under the USDA Conservation Reserve Program are denoted as CRP, and those previously managed under conventional soybean/corn rotation as AGR. Fields were planted to corn (C), switchgrass (Sw), or mixed-prairie (Pr), with an unchanged CRP grassland left for reference (CRP–Ref).

Site	Area (ha)	Textural class	Sand (g kg^{-1} soil)	Silt (g kg^{-1} soil)	Clay (g kg^{-1} soil)	Soil pH	CEC [meq $(100g)^{-1}$]	Bulk density (g cm^{-3})	Nitrogen (g kg^{-1} soil)	Carbon (g kg^{-1} soil)
CRP-C	19.5	Sandy loam	$664±29^{a}$	$257±24^{a}$	$80±8^{b}$	6.1^{a}	6.02^{ab}	1.58^{c}	2.0^{c}	21.2^{c}
CRP-Sw	17.9	Sandy loam	$688±25^{a}$	$265±23^{b}$	$48±6^{a}$	5.9^{a}	6.00^{ab}	1.66^{c}	1.6^{d}	18.5^{c}
CRP-Pr	13.1	Sandy loam	$697±53^{a}$	$245±42^{b}$	$58±12^{a}$	6.2^{a}	5.46^{b}	1.59^{c}	1.7^{d}	19.5^{c}
AGR-C	11.2	Sandy loam	$577±26^{b}$	$337±23^{b}$	$86±12^{b}$	6.4^{a}	8.08^{ab}	1.54^{a}	1.2^{a}	12.2^{a}
AGR-Sw	14.1	Sandy loam	$651±31^{a}$	$271±24^{ab}$	$79±12^{ab}$	6.4^{a}	7.07^{ab}	1.79^{b}	1.1^{a}	10.8^{b}
AGR-Pr	23.0	loam	$495±32^{c}$	$360±31^{b}$	$146±10^{c}$	5.8^{a}	8.60^{a}	1.69^{c}	1.4^{b}	13.5^{a}
CRP-Ref	9.1	Sandy loam	$583±28^{b}$	$342±25^{b}$	$75±8^{ab}$	6.2^{a}	6.50^{ab}	1.56^{c}	1.9^{c}	20.9^{c}

Means followed by same letters are not significantly different by t- test (p<0.05)
CEC – cation exchange capacity
Source: soil texture, pH, CEC, bulk density and total carbon and nitrogen - http://lter.kbs.msu.edu/datatables/372.

grass of Eurasian origin that is often planted in CRP lands. The fields were cut every three years but not harvested. The other three fields had been under conventional agriculture (AGR) soybean/corn rotation for several decades before conversion.

In 2009, all fields were converted to no-till soybean except for one CRP grassland that was maintained to serve as a reference site. The CRP grassland fields to be converted were treated with herbicide to kill the brome grass prior to planting soybean, and therefore annual ET for 2009 in these three fields was due to the grass before soybean planting plus the soybean crop afterwards. From 2010 to 2012 three of the former CRP sites and the three former AGR sites were planted to annual (corn) and perennial (switchgrass and mixed-prairie) grasslands, while the reference site remained unchanged (Fig. 1). Oats served as a nurse crop during the first year of switchgrass and prairie establishment. Corn was planted and harvested each year and the switchgrass and prairie fields were planted in 2010 and harvested from 2011 onwards. The dates of important management practices for each site during and following land use conversion are provided in Appendix A.

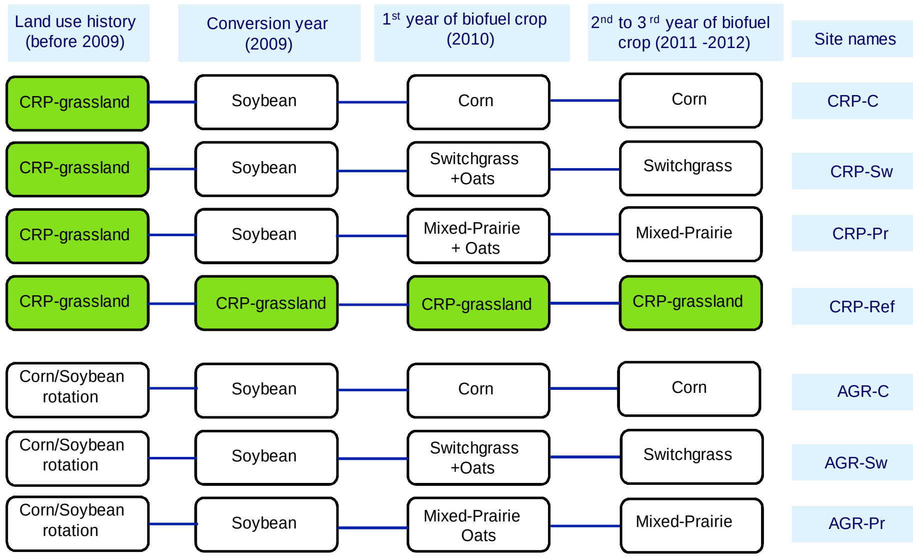

Fig. 1. Experimental design of the six bioenergy systems showing land use conversion from CRP and crop land to soybean in 2009, then to the three biofuel cropping systems starting in 2010. Also shown is the CRP-grassland site that was kept unchanged as a reference. ET measurements commenced in January 2009.

Eddy covariance and meteorological measurements

Continuous open-path eddy covariance (EC) and meteorological measurements were conducted over four years beginning in January 2009 at the seven fields to measure the total evaporative water flux (i.e., the sum of plant transpiration and evaporation from soil and canopy surfaces), hereafter referred to as ET. The EC towers were located at the center of each field with a fetch of at least 200 m in the prevailing wind direction. The height of the instruments was set according to the prevailing vegetation height (h) (usually > 1.5 m + h). The measurement system included a LI-7500 open-path infrared gas analyzer (IRGA, LI-COR Biosciences, Lincoln, NE) for H_2O and CO_2 concentration measurements and a CSAT3 three-dimensional sonic anemometer (Campbell Scientific Inc. (CSI), Logan, UT) for lateral, longitudinal, and vertical wind speed and sonic temperature measurements. The sensors were oriented towards the prevailing wind direction to minimize wind distortions due to supporting structures and were periodically checked and cleaned. The IRGAs were calibrated every four to six months using zero-grade nitrogen gas for zeroing H_2O and CO_2; and a dew point generator (Li-610, LI-COR Biosciences, Lincoln, NE) and standard CO_2–N_2 gas mixture for setting the H_2O and CO_2 spans, respectively. All eddy covariance measurements were conducted at 10 Hz and logged using a Campbell CR5000 datalogger. Additionally, we measured soil heat flux density (HFT3, CSI, Logan, UT) at 0.02 m below the soil surface using three randomly placed soil heat flux plates, soil temperature at three depths (0.02, 0.05 and 0.1 m) below the soil surface using CS107 probes (CSI, Logan, UT), and soil water content in the upper 0.3 m of the soil profile using a vertically inserted Campbell CS615 time domain reflectometry (TDR) probe. We realize that soil water content of the top 0.3 m of the soil profile is not a true measure of the soil profile water content. However, it serves as a robust indicator of soil water content changes due to soil evaporation and transpiration because most of the roots of the annual and perennial grasses are concentrated within this depth. Meteorological measurements of incoming and outgoing short- and long-wave radiation and air temperature and relative humidity were also made at each of the sites. Precipitation was measured at a nearby weather station (http://lter.kbs.msu.edu/datatables, accessed Mar. 2013) located about 4 km away from the nearest tower using a tipping bucket rain gauge (TE525WL-S: Texas Electronics, Dallas, TX). More information about instrumentation and measurements can be found in Zenone *et al*. (2011, 2013).

Data processing and gap filling

Half-hourly fluxes were computed using the software EdiRe (University of Edinburgh, v 1.5.0. 32, 2012) as a covariance of a scalar (sonic temperature, H_2O, or CO_2) and vertical wind speed (u_w). The raw data were screened using quality checks to remove out-of-range data generated due to bad weather, sensor and/or logger malfunction; spikes greater than four standard deviations;

and time lags between scalars (H_2O and CO_2) and u_w (McMillen, 1988). Planar fit rotation was used to align the three wind velocity components into a mean streamline coordinate system (Wilczak *et al*., 2001). The sonic temperature was corrected for pressure and water vapor concentration fluctuations (Schotanus *et al*., 1983). All eddy covariance outputs were computed using 30-min block averaging without detrending (Moncrieff *et al*., 2004). H_2O fluxes were corrected for frequency response (Moore, 1986) and air density fluctuations using the Webb-Pearman-Leuning terms (Webb *et al*., 1980), including the term for warming of the IRGA above ambient air temperature (Burba *et al*., 2008). Finally, non-stationarity (dividing the 30-min time series into 5-min intervals); flux-variance similarity and friction velocity thresholds (0.05 m s^{-1} and 0.1 m s^{-1} during the day and night, respectively) were used to ensure quality of the 30-min data by discriminating weakly developed turbulence (Foken and Wichura, 1996). Before friction velocity threshold selection criteria were applied, 17, 18, 26 and 23% for 2009, 2010, 2011 and 2012, respectively, of the H_2O flux data were either missing or did not pass the quality criteria test set as above and therefore were flagged as missing. A further 24, 22, 18 and 21% of the H_2O fluxes from the respective years were also removed after friction velocity threshold criteria were applied. The 30-min data that did not pass the quality assurance and quality test were excluded from the analysis and replaced by the standardized FLUXNET marginal distribution sampling (MDS) gap-filling algorithm of Reichstein *et al*. (2005; http://www.bgc-jena.mpg.de/~MDIwork/eddyproc/ accessed Dec. 2013).

To assess the overall quality of the computed fluxes, the energy balance closure was evaluated at 30-min intervals using the slope of the relationship between the turbulent fluxes ($H + LE$, where H and LE are sensible and latent heat energy flux densities, respectively) measured by eddy covariance and the independently observed available energy (R_n - G, where R_n and G are net radiation and soil heat flux density, respectively). Only good quality measurements were used in the analysis. The advected energy and physical and biochemical energy storage terms are not included in the equation, assuming that their values are negligible for croplands in relation to the other components of the equation (Wilson *et al.*, 2002b). We use the convention where radiative fluxes (R_n) directed towards the surface are positive, while non-radiative fluxes (all except R_n) are negative, and *vice versa*.

Means of growing season soil water content were analysed using one-way analysis of variance with repeated measures (ANOVA; $\alpha = 0.05$) using the statistical software R (R Development Core Team, 2013, version 2.15.3). Pairwise *t*-tests were conducted with α values adjusted using the Bonferroni correction. Uncertainties associated with gap filling techniques, friction velocity threshold selection criteria, and Monte Carlo simulations (95% confidence intervals) from the 30-min eddy covariance data were propagated into annual uncertainties (Goulden *et al.*, 1996; Moncrieff *et al.*, 1996) to facilitate comparison of fluxes between sites, biofuel crops and years. ET comparisons between two sites were made as follows:

$$ET_a - ET_b \pm \sqrt{(SE_a)^2 + (SE_b)^2}$$

where *ET* is the annual *ET*, *a* and *b* are two sites being compared, *SE* is the standard error arising from the propagated annual uncertainty. The lower and upper bounds were checked for significant differences based on whether the range includes zero or not.

RESULTS

Microclimate and ET

The daily and seasonal variations of ET over the reference site were highly correlated with the microclimatic conditions, soil water content, and phenology. The daily variations were specifically related to changes in net radiation (R_n), soil water content (*SWC*) in the upper 0.3 m of the soil profile, air temperature (T_{air}), water vapor pressure deficit (*VPD*), and wind speed (*U*) (Fig. 2) . The seasonal pattern of ET was distinctly divided into the cool season with low ET, when temperatures were low and plants were absent or inactive, and the growing season with peak ET in July – the month of highest mean air temperature. Soil water availability typically declined in the latter half of the growing season (Fig. 2), leading to a decrease in ET even though solar radiation and air temperature remained high. Among the four years, the 2012 growing season was particularly dry, and both *SWC* and ET showed greater soil water limitation in that summer. In contrast to 2012, soil water was not limited in 2010 due to uniform rainfall distribution throughout the growing season; the other two years were intermediate in soil water content during the growing season.

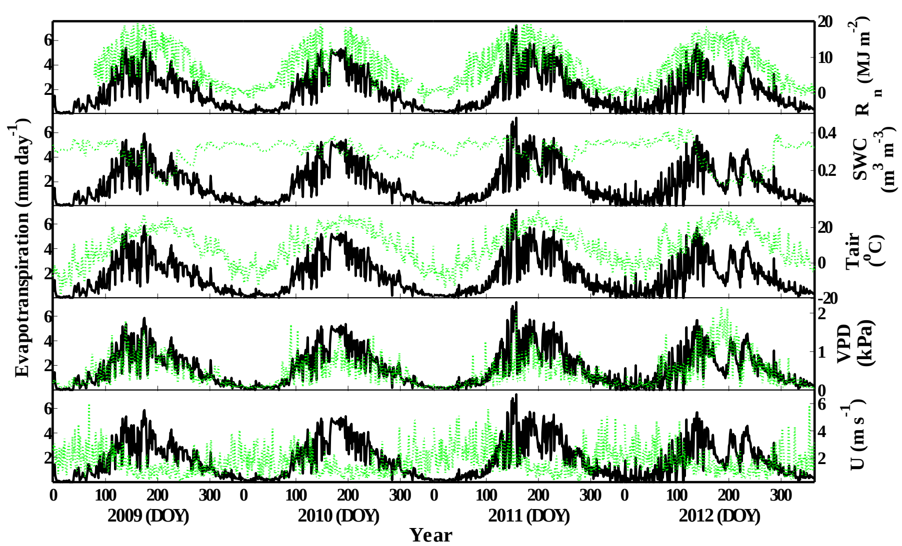

Fig. 2. Seasonal and interannual variation of the daily microclimatic variables [net radiation (R_n), average air temperature (T_{air}), average water vapor pressure deficit (*VPD*) and average wind speed (*U*)], average daily soil water content (*SWC*) for the top 0.3 m of the soil profile, and total daily ET over the CRP-Ref site from 2009 to 2012. T_{air} and *U* were measured at 2.75 m above the ground. Broken lines show weather variables and *SWC*, solid lines show ET, DOY is day of year).

Overall, total daily ET followed daily R_n throughout the season, with the exception of several dry spells when ET decreased sharply while R_n increased or remained constant, for example in the summer of 2009 and 2012. As expected, the seasonal change of average daily T_{air} followed the total daily R_n. Of particular note in this time series is the abnormally elevated T_{air} in March 2012 (Fig. 2), which set new records in the region. Net radiation was at its normal level during this time and the soils were water-saturated, and therefore changes in ET during that warm episode could be attributable mainly to changes in T_{air} (and *VPD*). However, the increase in ET during this time was relatively small because the plant canopy had not yet developed, and any plant growth that commenced was later suppressed by the return of normal cool conditions.

Energy balance

The energy balance closure for CRP-Ref site from 2009 to 2012 has slopes ranging between 0.73 and 0.84 (Fig. 3). Similar slopes were observed among the three biofuel cropping systems. This indicates an imbalance with the turbulent surface fluxes ($H + LE$) underestimated by 27 to 16% relative to the available energy (R_n - G).

ET in the biofuel cropping systems

The temporal changes of ET at all sites show the expected seasonality for this humid temperate climate region (Fig. 4), with shorter-term ET fluctuations, reflecting variable precipitation amount and timing among the four years. Sharp drops in ET during the growing season occurred in 2009 after herbicide application to the converted CRP fields in preparation for soybean planting, and in 2012 when soil water was drawn down to the limiting level.

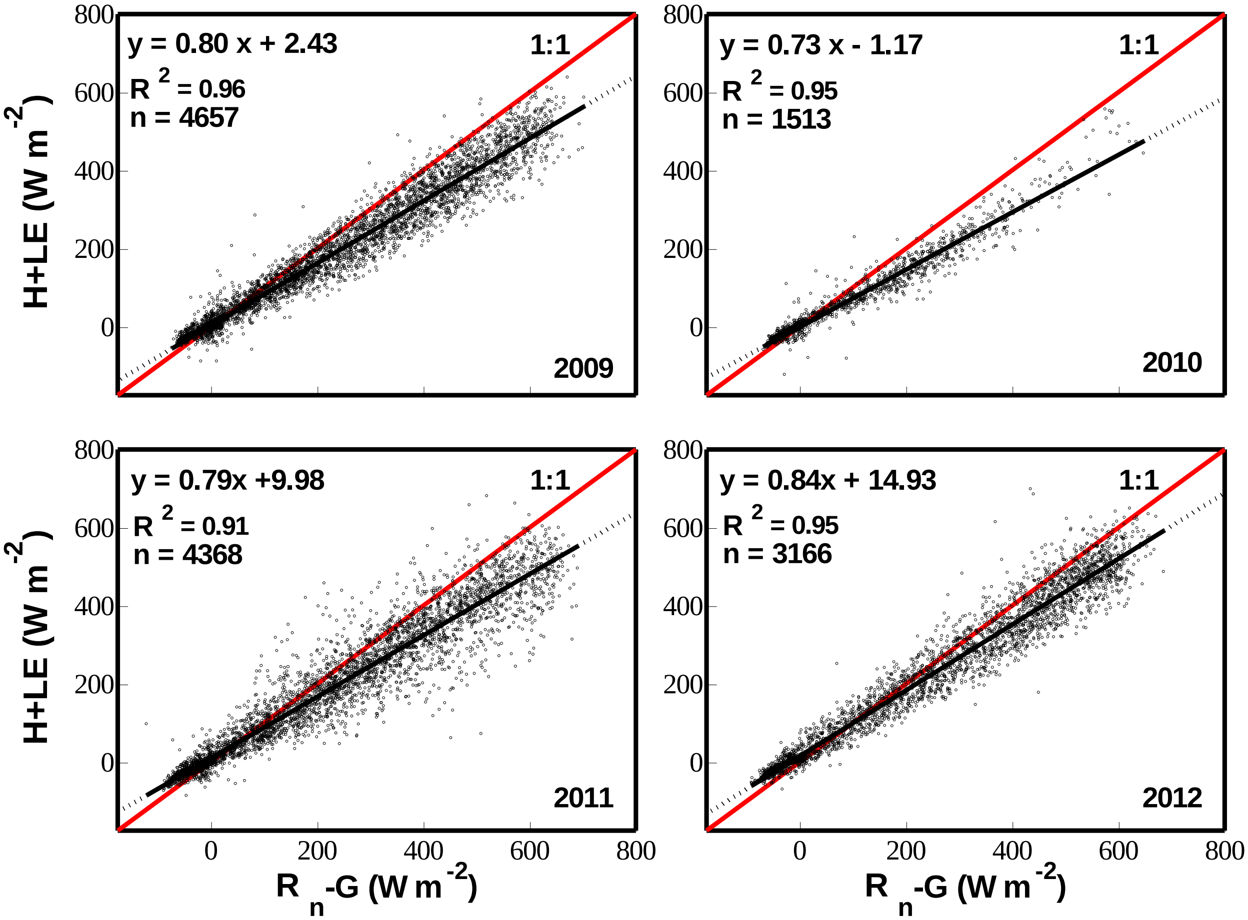

Fig. 3. Energy balance closure at the CRP-Ref site during the growing seasons of 2009 through 2012. The dashed lines indicate the 1:1 relationship whereas the solid with broken extension lines indicate the linear regression fit. The variables *H* and *LE* are sensible and latent heat flux densities, respectively, R_n is net radiation and *G* is soil heat flux density. Data represent measurements at 30-min intervals.

The total annual ET from 2009 to 2012, during and following land use conversion, ranged between 480 and 706 mm (Fig. 5), accounting for 45-77% of the annual precipitation (848-1063 mm; Nov-Oct). The higher annual precipitation in 2011 (Nov-Oct) did not result in consistently higher ET in the biofuel cropping systems, even though ET in the CRP-Ref grassland was higher that year.

The CRP-Ref grassland had the highest ET in each year (622-706 mm). Despite higher ET, the mean daily *SWC* of the top 0.3 m of the CRP-Ref soil profile was also consistently higher over the four years compared to all the biofuel crops, except during the summer dry spell of 2012 (Fig. 6). The drained upper limit of *SWC* in the root zone, as indicated by the *SWC* by the end of each winter, was higher in the CRP-Ref field than in the other fields, and the drained upper limit in the converted CRP fields was lower than in the AGR fields (Fig. 6). Clearly, there was more soil water available for plant uptake in the CRP-Ref field than in the other fields.

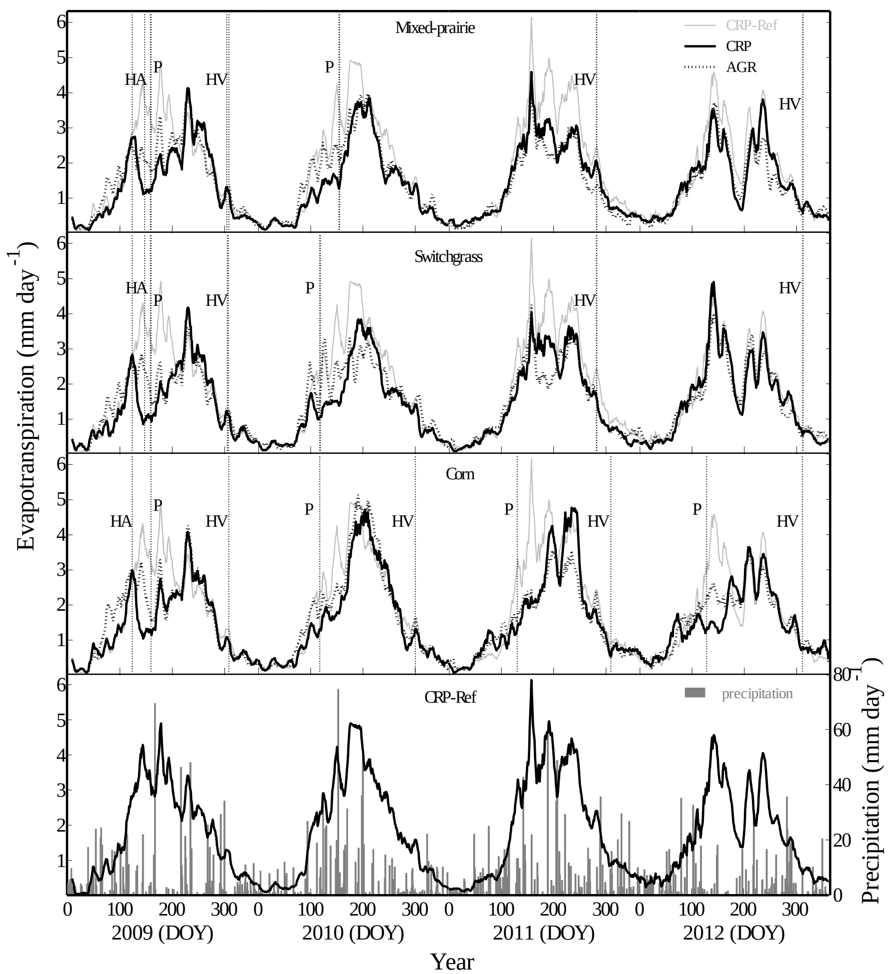

Fig. 4. Seasonal and interannual variation of ET (moving average with a period of ten days) and total daily precipitation at all sites from 2009 through 2012. ET time series for same biofuel crops at two sites with different land use histories and ET from the reference site are plotted together for comparison. Also shown are vertical lines representing management practices at each site and year (HA is herbicide application, P is planting, HV is harvest). The first two vertical lines from the left in 'Mixed-prairie' and 'Switchgrass' fields refer to HA dates on CRP and AGR lands, respectively (DOY is day of year).

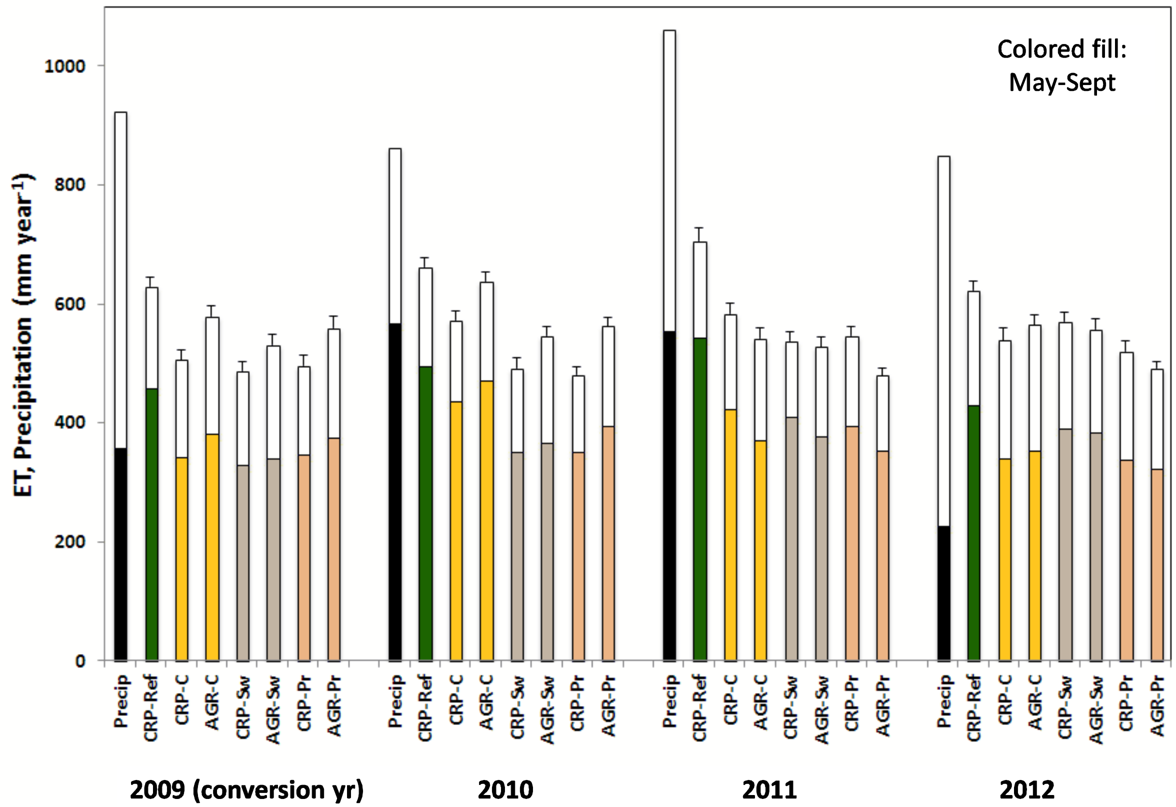

Fig. 5. Total annual ET (mm) for the biofuel crops and the reference grassland, and the annual precipitation from 2009 through 2012. The stacked bars indicate the growing season (May to Sept.; colored bars) and the rest of the year. Error bars show standard errors.

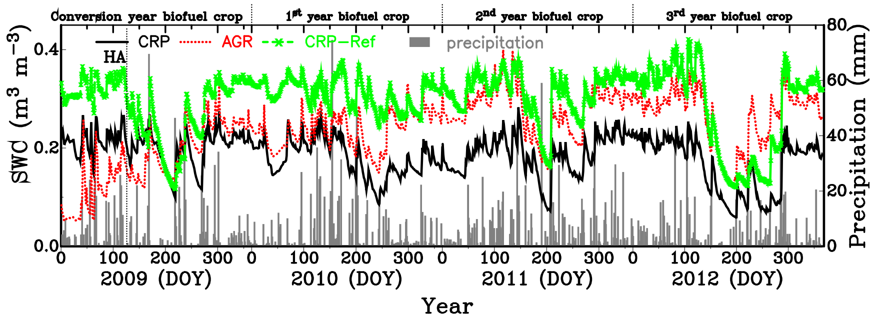

Fig. 6. Seasonal and interannual variation in average daily soil water content (*SWC*) for the top 0.3 m of the soil profile at the CRP-Ref, CRP and AGR fields and total daily precipitation from 2009 to 2012. The timing of herbicide application (HA) in 2009 at all converted CRP sites and the AGR-C site is marked by the vertical dotted line (DOY is day of year).

Annual ET in the annual and perennial biofuel crops varied between 480-639 mm with a mean of 555 mm over the three years despite large variations in precipitation and soil water content, and significant transformations from pre-existing land use to soybean, and then to corn and perennial crops in the converted fields (Fig. 5).

The fields converted from CRP grassland had lower ET in the first two years than those converted from row-crop agriculture (Fig. 5). The average daily *SWC* before land use conversion in 2009 was significantly greater in the CRP fields than that at the AGR fields (Fig. 6). However, soon after planting soybean (DOY 160) during the conversion year, the *SWC* at the CRP and AGR fields became similar and remained so through harvest.

In 2011, which was a wet year, the ET from the converted CRP fields was slightly greater than the ET from the AGR lands (Fig. 5). When ET rates from same biofuel crops were compared, all the former CRP fields showed significantly greater ET, except that the CRP-Sw was not statistically different from the AGR-Sw. The *SWC* of the AGR lands was, however, significantly greater ($p < 0.001$) than that of the CRP lands during this year.

In 2012, which was a drought year during the growing season, the total ET of the biofuel cropping systems was not markedly different from 2011 when *SWC* was much less limiting over the growing season (Fig. 5). ET consumed a larger percentage of the annual precipitation, with the mean for all seven fields of 65% in 2012 compared to 53% in 2011 (Table 2).

When annual ET from the biofuel crops is compared across land uses from 2010 through 2012 (Fig. 5), corn had the highest ET in 2010, which was the establishment year for switchgrass and prairie. There was no statistical difference between the ET values of corn and switchgrass in 2011 and 2012 although the prairie fields had significantly lower ET than corn in both years, and than switchgrass in 2012. Notably, the total range in ET across the biofuel cropping systems in 2011 and 2012 was not large despite the very different *SWC* availability in those two years.

Monthly ET from the crops showed differences that could be attributed to crop phenology and soil water availability (Fig. 7). The CRP-Ref field had much higher ET early in the growing season. In 2010, the year with the most consistent precipitation over the growing season, ET peaked in July at all sites. The mild and severe droughts experienced in 2011 and 2012, respectively, were reflected in the monthly water use patterns of all crops. This was less obvious in corn as it had a small canopy during these periods. From the second year of establishment onwards the seasonal pattern of the perennial cellulosic biofuel crops became similar to that of CRP-Ref, albeit with lower ET.

Table 2. The ratio of total annual evapotranspiration to precipitation from 2009 through 2012 for all biofuel crops and the reference site. Precipitation is the total for the 1 Nov-31 Oct period encompassing each growing season. See Fig. 1 for site names.

Year	CRP-C	CRP-Sw	CRP-Pr	AGR-C	AGR-Sw	AGR-Pr	CRP-Ref
2009	0.55	0.53	0.54	0.63	0.58	0.61	0.68
2010	0.66	0.57	0.56	0.74	0.63	0.65	0.77
2011	0.55	0.51	0.51	0.51	0.50	0.45	0.66
2012	0.64	0.67	0.61	0.67	0.66	0.58	0.73
Mean	0.60	0.57	0.56	0.64	0.59	0.57	0.71

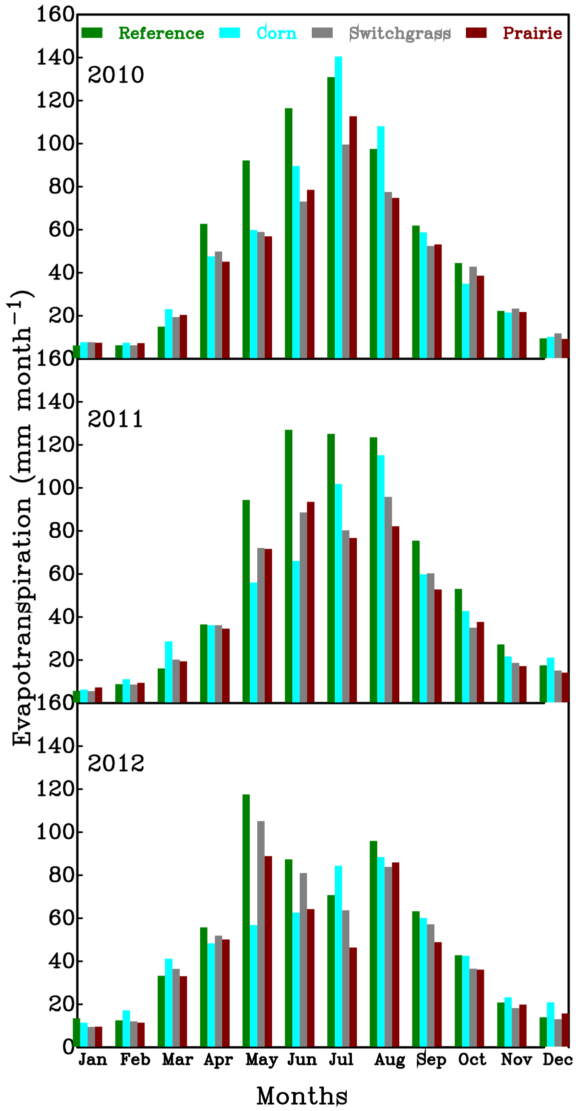

Fig. 7. Monthly totals of ET for the reference site and for each biofuel crop, averaged across the AGR and CRP fields, from 2010 through 2012.

DISCUSSION

The key finding of this study is the relative consistency of ET across the wide range of cropping systems and climate variability (Fig. 5). The ET of the annual grain crop—corn—was not greatly different from the ET of the perennial switchgrass and prairie cropping systems once the perennial systems had become established (2011 and 2012), despite a wide range of total annual precipitation. Thus our hypothesis that the perennial crops would use more water than corn was not supported. These observations do support the contention of Basso *et al*. (2012) that total crop ET over the growing season will be similar between corn and perennial grass biofuel crops, in contrast to a recent modeling study (Le *et al*., 2011) that concluded ET from perennial grasses would be significantly greater than corn (36% greater in the case of switchgrass).

This similarity in ET between crops of contrasting growth forms and phenologies may be due partly to the fact that at the onset of the growing season there was a similar amount of stored soil water that accumulated during the preceding cool season regardless of the amount of precipitation (i.e., the soils start at their drained upper limit, or “field capacity”). In a study of ET from different ecosystems, Sun *et al*. (2011) suggested that ET is greatly influenced by the soil water stored before the growing season. Over the growing season the plants use all of this stored water to the extent that they can draw on it, as well as most of any new precipitation during the growing season (some escapes by percolation after heavy rainfalls). Even in the face of growing-season drought and depletion of plant-available *SWC* in 2012, the total annual ET of all cropping systems in that year was similar to that of the two relatively wet growing seasons of 2010 and 2011 (Fig. 5). The perennial switchgrass and prairie had higher ET in May, when corn was just planted, and in June, but this difference was compensated by higher corn-ET in July and August (Fig. 7).

Herbicide application had a profound effect on ET and *SWC* during the conversion year, as expected (Figs. 4 and 6). Herbicide was applied in 2009 to prepare the converted (CRP and AGR) lands for soybean planting. All of the converted fields had lower ET compared to the CRP-Ref ET during this time (Fig. 4) because the live plant biomass was killed and transpiration completely halted. Soil evaporation was also reduced because the soil was covered with the newly herbicide-killed aboveground biomass. The decrease in ET was more marked in the converted CRP than that in the AGR fields because the converted CRP fields began with more live aboveground plant biomass and litter from the previous land use than did the AGR lands. The *SWC* also increased at the converted CRP lands a few days following herbicide application since the plants ceased taking water from the soil and the dead biomass shaded the soil surface, while at that time the *SWC* at the AGR and CRP-Ref sites decreased (Fig. 6).

The turbulent fluxes (*H* + *LE*) at our sites were underestimated by 16 to 27%, a result that falls within the typical 10 to 30% underestimation of surface fluxes reported in the eddy covariance literature (e.g., Twine *et al*., 2000; Wilson *et al*., 2002b; Oncley *et al*., 2007), with potential implications of underestimation of ET. While the lack of energy balance closure is not completely understood, potential reasons for underestimation of the turbulent fluxes by eddy covariance methods in comparison to the available energy at our sites could be due at least in part to errors related to mismatch of the source areas sampled by the turbulent fluxes and radiation sensors, lack of accounting for advection, and turbulent dispersive fluxes arising from the existence of organized planetary boundary-layer turbulent structures (Mahrt, 1998; Twine *et al*., 2000; Kanda *et al*., 2004; Leuning *et al*., 2012). Recent findings also indicate that the non-orthogonal 3D sonic anemometers used in this study may underestimate the vertical wind speed *w* by 10 to 12%, which, in turn, will underestimate the turbulent fluxes by 10 to 20% (Kochendorfer *et al*., 2012; Frank *et al*., 2013). Because these issues are likely to affect all the sites similarly, our conclusions about the relative differences among sites are valid in spite of the potential underestimation of ET.

The annual ET rates reported in this study are comparable to results from other studies for similar crops and climates. Fig. 8 summarizes annual precipitation versus annual ET for crops and years at our sites and for sites cited in this study provided annual precipitation and annual ET

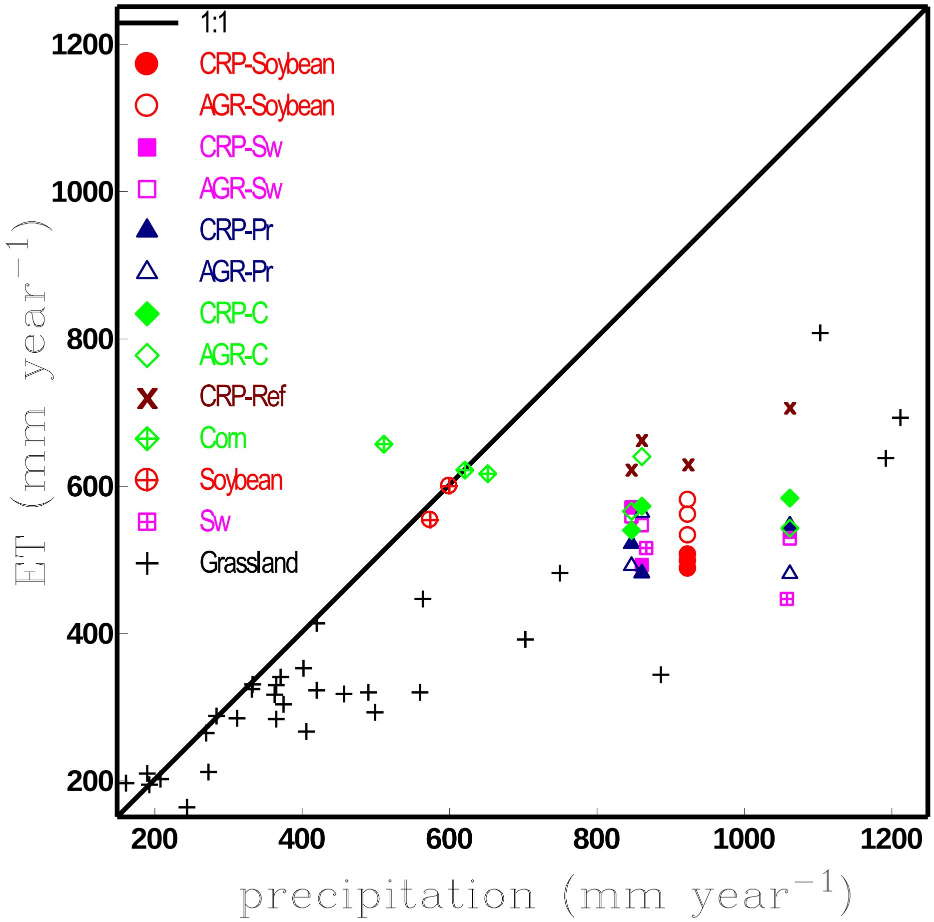

Fig. 8. Annual precipitation vs. annual ET for cropping systems and years in the current study compared with estimates for similar crops from the literature (Suyker and Verma, 2009; Skinner and Adler, 2010; Krishnan *et al.*, 2012; Huizhi and Jianwu, 2012; Brümmer *et al.*, 2012; Aires *et al.*, 2008; Li *et al.*, 2007; Ryu *et al.*, 2008 and Burba and Verma, 2005).

figures are available. Suyker and Verma (2009) reported annual ET of 616, 621 and 656 mm for rainfed corn, and 553 and 559 mm for rainfed soybean, in a five year corn-soybean rotation in the Midwestern US (Fig. 8). The annual ET for corn in our study was similar with a range between 539 mm during the drought of 2012 and 639 mm in 2010. The soybean ET in our study, although greatly influenced by pre-conversion plant growth and management practices during land conversion, was also similar with a range between 487 and 580 mm. The percentages of annual precipitation consumed by annual ET in the Suyker and Verma (2009) study were 128, 100 and 94% for corn and 100 and 96% for soybean, respectively, implying that there was excess water that must have come from sources other than the annual precipitation (e.g., ground water or interannual variations in soil water storage). Their study site in Nebraska is characterized by a drier climate than our study site but with similar growing season length, and yet the ETs for the respective crops in different years with variable annual precipitation were similar.

Skinner and Adler (2010) reported annual switchgrass ET ranging between 446 and 515 mm over four years of study, including the establishment year, in northeastern USA (Fig. 8). The switchgrass ET in our study was slightly higher, ranging between 492 and 570 mm. Skinner and Adler (2010) recognized that their ETs were relatively lower than reported ETs from the Great Plains and Midwest, and attributed this to a shorter growing season length, lower air temperature and lower solar radiation. Otherwise, the area had similar annual precipitation to our study area during the study period. Wagle and Kakani (2012) also reported a growing season (May to mid-November) ET of 450 mm for well-established switchgrass during a drought year (annual precipitation = 896 mm) in the south central US, where the growing season is slightly longer than in this study. The ET from switchgrass after establishment for the same time period in our study is similar, with a range between 419 (drought year) and 446 mm. These studies suggest that ET could slightly vary depending on growing season length and associated climate.

The range of total annual ET for the mixed grasslands from this study (480-563 mm for prairie; 622-706 mm for the CRP-Ref field) is higher than ET reported in many other grassland studies, but grassland ET has most often been studied in drier climates with less available soil water. Examples of ET ranges in the literature are shown in Fig. 8 and include (precipitation is given in parentheses): 250−341 mm (271−458 mm) and 177−300 mm (191−313 mm) for a warm temperate prairie and a semi-arid grassland, respectively, over four years in southeastern Arizona

(Krishnan *et al*., 2012); 194−413 mm (194−421 mm) for a semi-arid grassland in northeastern China over six years (Huizhi and Jianwu, 2012); 395 ± 90 mm (405 ± 160 mm) (mean ± standard deviation) for a grassland in western Canada over nine years (Zha *et al*., 2010); 329−446 mm (366−565 mm) for a grassland in western Canada over four years (Brümmer *et al*., 2012); 316 and 481 mm (364 and 751 mm) for a grassland in Portugal over two years (Aires *et al*., 2008); 163 mm (245 mm) for a temperate grassland in central Mongolia (Li *et al*., 2007); and 241−424 mm (376−888 mm) for a western US grassland over six years (Ryu *et al*., 2008). In all the above studies, ET reflects the amount of precipitation received. The percentage of precipitation consumed in ET is higher on the lower end of the precipitation range than on the upper end of the range. This is consistent with our finding that the ET to precipitation ratio was highest in the drought year and lowest in the wettest year. In a more comparable humid climate in the south central US, Burba and Verma (2005) found annual ET of 807, 637 and 692 mm for tallgrass prairie in three years of study (Fig. 8). However, their location had a longer growing season and greater precipitation (1104, 1193 and 1213 mm for the three years, respectively) than this study, and the grasses were mainly composed of warm season C_4 species. The higher ET in the first year (with the lowest annual precipitation) was attributed to a large fraction of the annual precipitation falling in summer, thus maintaining adequate soil water content to allow ET to proceed at a higher rate during the season of highest evaporative demand.

Fewer studies are available that compare ET among different potential biofuel cropping systems. Hickman *et al*. (2010), using a residual energy balance approach, reported 25% higher growing-season ET in switchgrass than that of corn in the Midwestern US, although the corn had a shorter growing season and early-spring ET before planting corn was not included. In a similar climate, Zeri *et al*. (2013) presented data that indicate that ET from biofuel crops decreased in the following order: corn, prairie and switchgrass in the second year of establishment of the cellulosic biofuel crops; prairie, switchgrass, soybean in the following year; and switchgrass, prairie and corn in the last year. This agrees with our study in that ET in the perennial biofuel crops was not always greater than ET in the annual crops. The magnitude of ET in both the above studies, however, was greater than in our studies, except during one of the years in Zeri *et al*. (2013). This could be due to differences in climate, planting and harvest dates, crop variety, species composition (in prairie), establishment phases (in the perennial crops), etc. In general, most ET studies conducted in different ecosystems indicate lower ET than that reported in Zeri *et al*. (2013). For example, Brümmer *et al*. (2012) analyzed ET data for sites containing nine mature forests, two peatlands and a grassland across an east–west transect in Canada. Although annual precipitation varied between 250 and 1450 mm among sites, the maximum ET did not exceed 500 mm regardless of the precipitation amount. Most of the studies cited above also fall within this range.

Our finding that ET consumed 45-77% (mean=60%) of the annual precipitation in the seven fields (Table 2) indicates that the balance would either recharge the groundwater or leave the fields by overland flow. In the cropping systems investigated here, that balance would be proportionately larger in years of higher precipitation because we observed ET to be consistent across years of variable precipitation. Percolation out of the root zone is likely most important in our study area; overland flow is relatively small compared to infiltration in these sandy loam soils, and most streamflow in the area is generated by groundwater discharge (Hamilton, *In press*).

We conclude that water use by annual and perennial crops was not greatly different across different years with highly variable growing-season precipitation and soil water availability. The humid temperate climate of our study site is typical of rain-fed, row-crop agricultural regions in temperate climates, including the US Corn Belt. Our results suggest that large-scale conversion of row crops to perennial biofuel cropping systems (or *vice versa)* may not strongly alter terrestrial water balances in the short term. Longer-term research on these cropping systems (with annual harvesting) is required to understand whether the current conclusions hold over the lifetime of the perennial crops, or if ET rates would diverge over time, perhaps as a result of the expected continuing accumulation of soil organic matter in the perennial grassland systems.

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Appendix A. Major agronomic management practices and the time (day of year) of their implementation from 2009 through 2012.

Year	Activity	CRP-C	CRP-Sw	CRP-Pr	AGR-C	AGR-Sw	AGR-Pr
2009	**Herbicide**						
	Glyphosate 2.85 kg ha^{-1}	125; 184	125; 184	125; 184	126; 205	149; 205	149; 205
	Planting	161	161	161	160	160	160
	Harvest	310	309	310	307	307	306
2010	**Herbicide**						
	Herbicide mix*	119	-	-	120	-	-
	Fertilizer						
	P_2O_5 + K_2O, 168.5 kg ha^{-1}	95	-	-	95	-	-
	28% liquid N_2, 112 kg ha^{-1}	160	May (57 kg ha^{-1})†		165	May (57 kg ha^{-1})	
	‡Planting	119	119	157	120	120	156
	Harvest	302	-	-	294	-	-
2011	**Herbicide**						
	herbicide mix	133	-	-	126	-	-
	Fertilizer						
	P_2O_5 + K_2O, 168.5 kg ha^{-1}	104	-	-	104	-	-
	28% liquid N_2, 34 kg ha^{-1}	132	-	-	125	-	-
	28% liquid N_2, 134 kg ha^{-1}	172	188 (57 kg ha^{-1})		172	188 (57 kg ha^{-1})	
	Planting	132	-	-	125	-	-
	Harvest	311	284	284	307	284	284
2012	**Herbicide**						
	herbicide mix	129	-	-	127	-	-
	herbicide mix	-	-	-	167	-	-
	Fertilizer						
	P_2O_5 + K_2O, 168.5 kg ha^{-1}	102			102		
	28% liquid N_2, 146 kg ha^{-1}	167 (123 kg ha^{-1})	115 (57 kg ha^{-1})		166	115 (57 kg ha^{-1})	
	28% liquid N_2, 34 kg ha^{-1}	174 (60.5 kg ha^{-1})	-		173	-	
	Planting	129	-	-	127	-	-
	Harvest	312	313	313	308	313	313

*Herbicide mix – a Lumax (5.9 L ha^{-1}), Atrazine 4L (0.78 L ha^{-1}), Gramoxone Inteon (2.33 L ha^{-1}) and ammonium sulphate (0.92 kg ha^{-1}) or similar mixture.

†Application rates are given in brackets – if they differ than what is given under the activity section.

‡Oats planted as a nursery crop along with switchgrass and prairie during the first year of establishment (2010).